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Photograph by G. A. Corby

MR P. J. MEADE, O.B.E.

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RETIREMENT OF MR P. J. MEADE, O.B.E.

On the retirement of Mr P. J. Meade, O.B.E., as Director of Services and Deputy to the Director-General, on 30 September 1973, after 37 years of distinguished service, the Office lost one of its most effective and influential figures of the post-war era.

Patrick Meade joined the Office in 1936 after graduating from Imperial College with first-class honours in mathematics and receiving the Lubbock Memorial Prize of London University. He began his meteorological career at the Empire Flying Boat Base, Hythe (Hants), joined the Reserve of Air Force Officers (Meteorological branch) in 1937 and, in 1939, entered on a period of distinguished war service with appointments as Senior Meteorological Officer, G.H.Q. Home Forces, Chief Meteorological Officer, Mediterranean Air Forces, and Chief Meteorological Officer, Air Command South East Asia. His outstanding work for the Allied Air Forces in North Africa and Italy, where he achieved a high degree of co-operation with the 15th U.S. Air Force, was recognized by the award of the O.B.E. in 1944.

After leaving the RAF in 1947 with the rank of Group Captain, Mr Meade returned to the Office as Personal Staff Officer to the Director, Sir Nelson Johnson, and in 1948 became Head of the Training School, first at Alexandra House and later at Stanmore.

There then followed a series of important appointments and rapid promotions. He was Chief Meteorological Officer, London Airport, from 1952 to 1955 during a period of rapid expansion of civil aviation. In 1955 he was promoted to Assistant Director in charge of Special Investigations which, at that time, were much concerned with radioactive fall-out from nuclear weapons and atmospheric pollution. Here Meade made good use of his first real opportunity to carry out sustained research and investigations, and when he was nominated for the Imperial Defence College in 1958 it was clear that he was destined for higher things.

During the last seven years his outstanding qualities of leadership, initiative, foresight and drive have been of crucial importance to the Office during a period of rapid change and modernization. He has been largely responsible for the successful and smooth introduction on a routine basis of computer methods of weather forecasting which has led to wholesale reorganization and centralization of the meteorological services and the re-training of large numbers of staff in new techniques and methods of working. Despite the heavy load imposed by all these new developments and the day-to-day responsibility of directing more than 3000 staff, Mr Meade has found the

time and energy to play a very prominent part on the wider international scene. His work in WMO as Chairman of the Executive Committee Panel on Ocean Affairs, and his efforts at both national and international level on behalf of hydrometeorology will have a lasting influence in strengthening the links between these two disciplines and meteorology. Mr Meade has also been deeply involved from the very beginning in the proposals to establish a European Centre for medium-range weather forecasting, his efforts being crowned by the decision to locate this at Shinfield Park, near Reading.

In the last year or two he has devoted much of his energy and advocacy towards ensuring a continuance of the North Atlantic Ocean Station scheme after the existing agreement expires in 1975 and to preparing a case for the Office to build new ships.

All this adds up to an outstanding record of activity and accomplishment which will leave its imprint for many years to come. Meteorology in general, and the Office in particular, owes Patrick Meade a great debt. Much of his achievement is already visible; the rest provides us with a firm foundation on which to build in the future.

Mr Meade's many colleagues and friends, at home and abroad, will, I know, join me in wishing him and Mrs Meade a long, active and happy retirement.

B. J. MASON

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SOME MEASUREMENTS OF CUMULONIMBUS TOPS IN THE PRE-MONSOON SEASON IN NORTH-EAST INDIA

By S. G. CORNFORD and C. S. SPAVINS
(Meteorological Office, Bracknell and Royal Aircraft Establishment, Bedford)

Summary. The heights of some cumulonimbus clouds forming during the pre-monsoon season in north-east India have been carefully measured using airborne radar, cameras and horizon gyroscopes. They were found to extend up to at least 65 000 ft (20 km). One top rose at 1200 ft/min (6 m/s) from an initial height of 60 000 ft. The best indicator of the heights of such storms was the parcel-theory top. At the equilibrium level some parcel-theory updraughts exceeded 100 m/s. High tops may be more frequent in the area than ground-based radar observations have indicated.

Introduction. The severe local convective storms of Bengal and neighbouring parts of the Indian subcontinent are of concern to the inhabitants, shipmasters,[1] aviators[2,3] and meteorologists[3–9] alike. Occurring mostly in the pre-monsoon period from April to early June, the storms usually approach the densely populated area around Calcutta from between west and northwest and are first felt as a squall from that direction. These nor'westers occur in a geographical situation similar to that of the severe local storms in the United States of America, where an extensive dry continental area has a bay of warm sea lying to the south and south-east. In the United States severe local storms are known to reach heights of over 60 000 ft (18 km)[10,11] and to extend into the stratosphere by 20 000 ft or more.[10] This paper reports measurements of similar heights for storm tops in north-east India, based on the use of an airborne radar and camera system and amplifies an earlier report by Spavins.[12] The highest top measured was at 65 000 ft (20 km).

Storm tops at such high levels need to be avoided by cruising supersonic airliners. The pilot's main cue to a storm ahead will be an echo seen on his radar screen. Some of the work on turbulence associated with storm tops has been directed towards relating such echoes and the safe boundaries of storms. Burnham and Spavins have established that turbulence may extend into the clear air for up to 15–20 miles (25–30 km) around a visible storm and up to 5000–10 000 ft ($1\frac{1}{2}$–3 km) above its top.[13,14]

This paper also reports some measurements of visible storm tops and the tops of corresponding radar returns seen from an aircraft close to the storm and from the ground.

There are several quantities which forecasters could supply and which pilots could use to judge whether a storm seen ahead on the aircraft's radar will be high enough to obstruct the projected flight path. As in Roach's study for the U.S.A.[10] the highest tops reported here usually approached the level predicted by the parcel theory. In determining that level practically, though, it was necessary to find which of the local surface temperatures and humidities were most appropriate.

Bhattacharyya and De[15] and Rakshit (private communication) have summarized regular observations made with a radar at Dum Dum Airport, Calcutta. These observations are compared with the present measurements.

Observations.

(a) *Equipment.* A DC-3 aircraft, operated by Fairey Surveys Ltd on behalf of RAE Bedford, was fitted with a motorized single-lens reflex Hasselblad camera to photograph the clouds. The camera was fixed, pointing forward and horizontally when the aircraft was flying in a normal attitude. Its nominal focal length of 80 mm was checked at RAE Farnborough and found to be correct to within less than 0·1 mm. A similar camera was used to photograph the outputs of other specially fitted instruments: the PPI (Plan Position Indicator) display of a gyroscopically stabilized, forward-facing, 31-mm radar; the angle of tilt of the radar; a clock showing Greenwich Mean Time and a counter. Other gyroscopes measured the pitch and roll attitudes of the aircraft and so provided a reference horizon to be used in interpreting the cloud photographs. The output from these gyroscopes was recorded on a galvanometer oscillograph, together with pressure height, indicated airspeed, normal acceleration, elapsed time, and synchronization pulses. The tops of some storms were also measured from the ground using the 31-mm radar at the meteorological office at Dum Dum Airport. The characteristics of this radar and of the airborne radar are listed in Appendix I.

(b) *Period and area of operation.* Between 12 May and 3 June 1969 15 flights from Dum Dum Airport, Calcutta, yielded useful information on 51 storms. All the measurements were made between 1319 and 1810 Indian Standard Time (IST). The storms were in the area shown in Figure 1.

(c) *Observational routine.* The aircraft was flown on days when the forecasters at Dum Dum expected cumulonimbus within about 550 km (300 nautical miles) to the north and west of Calcutta. In the area where the biggest clouds seemed likely the pilot tried to select a large isolated storm and to fly straight towards it at a height of about 6 km (20 000 ft) and from 55 to 75 km (30 to 40 n. mile) on the upwind side. Observations were usually completed when the aircraft was more than 40 km from the storm. In most

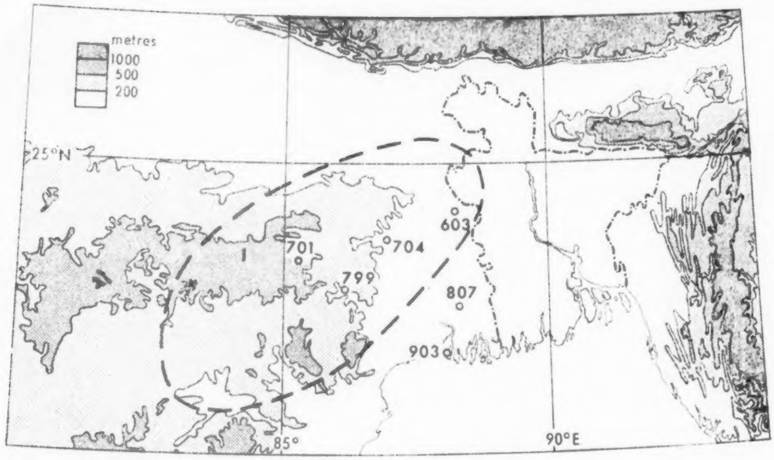

FIGURE 1—MAP SHOWING THE AREA OF OPERATIONS OVER NORTH-EAST INDIA

All the measured storms were in the area enclosed by the heavy pecked line. The six stations are those used to give the regional temperatures and humidities discussed in the section dealing with comparison of the measured storm tops with heights given by some commonly used techniques. They are

603	Berhampore	19 m	799	Jamshedpur	131 m
701	Ranchi	652 m	807	Calcutta	6 m
704	Asansol	126 m	903	Saugor Island	3 m.

instances the pilot then chose another cloud to study, though sometimes several measurements were made of the same cloud. In each case simultaneous photographs were taken of the cloud and of the PPI display of the radar with its scanner horizontal (see Plate I). The scanner was then tilted down until the return from the ground beyond the storm could be photographed and afterwards raised in one-degree steps until the return from the storm disappeared. A photograph of the display was taken with the scanner in each position to give a series of nearly horizontal sections through the depth of the storm (see Plate II — the operator was instructed to allow the afterglow from the paint at one elevation angle to die away before photographing the echo made with the scanner at the next higher angle). Finally, the scanner was returned to the horizontal and simultaneous photographs were again taken of the radar display and the cloud (see Plate III). The whole sequence usually took less than two minutes.

(d) *Analysis of photographs.* From the photographs of the cloud and the radar display the heights of the storm tops were deduced by the method described in Appendix II. Fundamentally the radar was used to give the horizontal range of the storm and the cloud photograph was used to measure the angular elevation of the storm top above the aircraft. Corrections were made to allow for the pitch and roll attitudes of the aircraft and for the curvature of the earth but not for any leaning of the cloud towers. The geometric height of the aircraft was deduced from its pressure height and the

D-value* calculated from the afternoon radiosonde ascent from Dum Dum.

The height of the top of each visible cloud at the beginning and end of each run was assessed separately by two analysts. Their agreed results are listed in columns 4 and 5 of Table I.

The 'radar height' for each storm top was derived from the sequence of photographs taken as the scanner swept in one-degree steps from the bottom to the top of the storm and is shown in column 6.

The errors of the various measurements are assessed in Appendix III. The random error of a single entry in columns 4 and 5 of Table I is about ± 1500 ft (450 m), unless a greater error is indicated by columns 7 and 8. The figures in these two columns are due to a third analyst who re-assessed the data, knowing the first assessment. His check was especially useful in finding possible gross errors arising from interpretation of the photographs. His figures have been adjusted slightly to allow for the D-value correction and the correction for the curvature of the earth.

All the visible tops are probably slightly underestimated because of a systematic effect of attenuation of the 31-mm radar beam in precipitation. This will have produced an apparent shift of the centre of strong echoes towards the radar. It is not easy to assess the size of the shift. One of a mile or two would be equivalent to an underestimate of from 2000 to 4000 ft (600–1200 m) in the cloud top.

The underestimate has not been allowed for in deciding on a 'highest agreed measured cloud top' (Z_s) which is tabulated for each day in column (vii) of Table II. The percentage frequency with which Z_s equalled or exceeded various heights is shown in Figure 2. On arithmetic-probability axes, Figure 2 also shows the percentage frequency with which the highest radar measurement, Z_r, made by the aircraft each day equalled or exceeded various heights. Both Z_s and Z_r fit a normal distribution quite well. However, although the median Z_r is below the median Z_s, the Z_r curve is much steeper. This is thought to be caused by the greater errors in measuring Z_r.

The heights of the tops of the visible clouds have been used to assess the average rate of rise during the two minutes or so of each run. Each height is, of course, an absolute measurement and the change is the small difference between two large quantities. However, each height was initially determined independently by two different analysts and then by the third. The agreement between the three of them as to the sign and magnitude of the change of storm height is encouraging, with a mean difference between the first two analysts of 60 ft/min (0·3 m/s) and a standard deviation about that mean of 600 ft/min (3 m/s).

The variation of rate of rise (and sink) has been examined both with initial height and with initial depth below the parcel-theory top, Z_p. In both instances there was no relationship. They showed, however, as is natural if the tallest tops were chosen, that there was a slight tendency for tops to sink during the run.

The greatest rate of rise measured when all three analysts agreed on the height of the storm top was 1700 ft/min (± 600 ft/min) from an initial height of 57 000 ft. A rate of 1200 ft/min (6 m/s) was measured from an initial

* The D-value is the difference, D, between the actual height, Z, above mean sea level, of a particular pressure surface and the pressure altitude, Z_p (the height of the same surface in the International Civil Aviation Organization Standard Atmosphere) i.e. $D = Z - Z_p$.

TABLE I—COMPARISON OF STORM TOP HEIGHTS IN NORTH-EAST INDIA IN THE PRE-MONSOON SEASON OF 1969 AND VARIOUS PREDICTORS, IN THOUSANDS OF FEET

1 Date and flight number	2 Time IST	3 Storm identification letter	4 Photogrammetric height, 1st assessment. Start of run	5 Photogrammetric height, 1st assessment. End of run	6 Aircraft radar height	7 Photogrammetric height, Ludlam's assessment. Start	8 Photogrammetric height, Ludlam's assessment. End	9 Radar height of top, measured from ground at Dum Dum	10 Z_p 1730 IST	11 Z_e 1730 IST	12 Height of tropopause 1730 IST	13 Highest top given in forecast
12 May	1633	A	42	41	44	Tops at 63 to 61 in storm behind A		—				
(2)	1655	B	64	63	57	As col. 4	Doubtful of col. 5	—	61	49	55	39
	1702	C	—	55	58	As col. 4	Doubtful of col. 5	—				
	1810	D	61	—	58	As col. 4	—	—				
13 May	1646	E	—	—	62	—	—	—				
	1655	F	—	—	39	—	—	—				
(3)	1704	E	—	—	50	—	—	—	65	51	54	46
	1723	F	—	—	39	—	—	—				
	1735	G	—	—	45	—	—	—				
	1747	F	—	—	53	—	—	—				
16 May	1532	H	58	62	54	Fuzzy dome, reliably about 62		—				
	1538	I	62	65	55	As col. 4	Doubtful of col. 5	—				
(5)	1546	I	59	68	53	As col. 4	Doubtful of col. 5	—				
	1622	J	54	54	56	As col. 4	34	—				
	1630	J	— See note 3	—	45	55	59	—				
	1638	J	55	56	53	Main top around 60		—	67	53	55	30
	1647	J	56	53	49	51	As col. 5	—				
	1658	J	57	58	56	As col. 4	As col. 5	—				
	1708	J	56	54	55	As col. 4	As col. 5	—				
	1718	J	56	57	57	As col. 4	As col. 5	—				
	1722	K	52	53	43	Doubtful of col. 4	Doubtful of col. 5	—				
	1733	J	51	54	51	As col. 4	As col. 5	—				
17 May	1533	L	46	43	40	49	50	—				
	1554	M	51	55	44	As col. 4	As col. 5	—				
(6)	1602	M	54	—	51	As col. 4	—	—				
	1613	N	60	55	58	As col. 4	As col. 5	—	64	51	55	33
	1630	N	54	49	41	As col. 4	Doubtful of col. 5	—				
	1645	N	50	47	45	51 is anvil, tops may be higher		—				
	1659	N	47	45	36	63 (different storm from cols. 4 & 5)	58	—				
19 May	1610	O	58	54	47	As col. 4	As col. 5	—				
	1613	P	—	43	38	—	As col. 5	—				
(7)	1623	O	56	55	52	As col. 4	As col. 5	—				
	1650	O	60	57	57	As col. 4	As col. 5	—				
	1700	O	—	—	—	—	—	30*	63	53	52	Cb forecast. Tops not given
	1702	Q	—	—	53	—	—	—				
	1726	Q	—	—	49	—	—	—				
	1730	Q?	—	—	—	—	—	36*				
	1730	R	—	—	48	—	—	—				
	1754	Q	53	51	46	As col. 4	As col. 5	—				

1	2	3	4	5	6	7	8	9	10	11	12	13
20 May	1551	S	—	—	47	—	—	—				
	1600	T	—	—	45	—	—	—				
(8)	1609	U	—	—	48	—	—	—	67	54	53	39
	1617	T	—	—	40	—	—	—				
	1635	V	—	—	48	—	—	—				
21 May	1427	X	61	61	68	As col. 4	As col. 5	—				
	1440	X	61	61	61	Slight doubt about both		—				
(9)	1452	Y	46	43	43	As col. 4	As col. 5	—				
	1504	X	57	58	62	As col. 4	As col. 5	—	69	55	53	46
	1516	X	61	57	59	As col. 4	Doubtful of col. 5	—				
	1527	X	60	60	63	As col. 4	Doubtful of col. 5	—				
	1638	Z	55	54	40	As col. 4	As col. 5	—				
22 May	1345	A_2	51	52	53	As col. 4	As col. 5	—				
	1409	B_2	46	46	38	As col. 4	As col. 5	—				
(10)	1425	A_2	35	35	36	As col. 4	As col. 5	—				
	1430	B_2	—	—	—	—	—	23*				
	1435	A_2	52	53	49	As col. 4	As col. 5	—				
	1440	B_2	57	58	56	As col. 4	As col. 5	—				
	1449	B_2	—	—	—	—	—	> 30, < 46**	68	55	55	39
	1450	A_2	—	—	—	—	—	> 35**				
	1455	B_2	67	64	64	65	62	—				
	1510	B_2	—	—	—	—	—	28*				
	1526	B_2	60	61	62	As col. 4	As col. 5	—				
	1542	C_2	57	57	59	As col. 4	As col. 5	—				
	1546	B_2	60	61	60	60	62	—				
23 May	1348	D_2	46	46	45	As col. 4	As col. 5	—				
	1410	E_2	60	61	71	62	63	—				
(11)	1421	F_2	57	57	57	As col. 4	As col. 5	—				
	1425	F_2	—	—	—	—	—	43*				
	1431	F_2	—	—	—	—	—	> 31, < 50**				
	1431	G_2	—	—	—	—	—	> 36, < 56**				
	1432	E_2	—	—	—	—	—	> 47**				
	1434	F_2	—	—	—	—	—	43*				
	1434	G_2	57	58	55	As col. 4	As col. 5	—	61	50	55	Cb forecast Tops not given
	1437	G_2	—	—	—	—	—	> 33, < 59**				
	1441	G_2	—	—	—	—	—	43*				
	1443	E_2	66	64	57	Doubt values in cols. 4 and 5		—				
	1445	G_2	—	—	—	—	—	> 39**				
	1447	E_2	—	—	—	—	—	53*				
	1505	E_2	—	—	—	—	—	54*				
	1550	H_2	57	56	53	58	As col. 5	—				
	1600	H_2	—	—	—	—	—	46*				
	1612	H_2	58	58	53	As col. 4	As col. 5	—				
28 May	1319	I_2	56	58	56	As col. 4	As col. 5	—				
	1334	I_2	61	64	59	As col. 4	Doubtful of col. 5	—	64	52	55	39
(14)	1353	I_2	58	56	55	Doubtful of cols. 4 and 5		—				
30 May	1612	J_2	—	35	36	—	—	—	65	52	55	39
(15)	1616	J_2	37	37	39	—	—	—				

TABLE I—*continued*

1 Date and flight number	2 Time IST	3 Storm identification letter	4 Photogrammetric height, 1st assessment. Start of run	5 Photogrammetric height, 1st assessment. End of run	6 Aircraft radar height	7 Photogrammetric height, Ludlam's assessment. Start	8 Photogrammetric height, Ludlam's assessment. End	9 Radar height of top, measured from ground at Dum Dum	10 Z_p 1730 IST	11 Z_e 1730 IST	12 Height of tropopause 1730 IST	13 Highest top given in forecast
31 May	1434	K_2	41	43	42	As col. 4	As col. 5	—				
	1440	L_2	49	49	41	Doubtful of cols 4 and 5		—				
(16)	1454	L_2	52	50	46	As col. 4	As col. 5	—				
	1521	M_2	58	53	54	As col. 4	As col. 5	—	62	50	55	33
	1530	M_2	—	—	—	—	—	40*				
	1540	M_2	71	> 77	63	Doubtful of cols. 4 and 5		—				
	1602	N_2	55	55	54	As col. 4	As col. 5	—				
	1631	O_2	49	55	50	As col. 4	As col. 5	—				
	1636	O_2	53	53	53	As col. 4	Doubtful of col. 5	—	62	50	55	33
	1652	N_2	58	57	54	As col. 4	As col. 5	—				
	1718	P_2	56	54	55	As col. 4	As col. 5	—				
	1732	P_2	52	51	47	As col. 4	As col. 5	—				
1 June	1356	Q_2	55	54	59	57	56	—				
	1406	R_2	60	63	62	As col. 4	Doubtful of col. 5	—				
(17)	1424	S_2	59	63	61	As col. 4	As col. 5	—				
	1432	Q_2	59	59	61	As col. 4	Slightly doubtful of col. 5	—	65	53	55	39
	1509	S_3	66	65	68	65	64	1500–1520: Tops in same area 56–66*				
2 June	1424	T_2	53	52	53	As col. 4	As col. 5	—				
	1438	T_2	57	57	51	Doubtful of cols. 4 and 5		—				
(18)	1509	U_2	53	51	47	As col. 4	As col. 5	—				
	1634	W_2	56	58	54	As col. 4	Doubtful of col. 5	—	67	54	55	46
	1648	W_2	—	—	—	—	—	54*				
	1648	X_2	—	—	—	—	—	> 47**				
	1703	X_2	55	56	48	Slight doubts about cols. 4 and 5		—				
3 June	1405	Y_2	60	61	53	As col. 4	Doubtful of col. 5	—				
	1417	Z_2	61	54	48	Doubtful of cols. 4 and 5		—				
(19)	1430	Z_2	61	63	52	Slight doubt about col. 4	Doubtful of col. 5	—	67	55	55	Cb forecast Tops not given
	1509	A_3	60	57	41	As col. 4	As col. 5	—				

Notes : (1) In column 3 a question mark denotes some doubt about whether the ground and aircraft measurements refer to the same storm.
(2) In column 9 a single asterisk denotes that the measurement was made by the usual method employed at Dum Dum. A double asterisk denotes a top deduced from a sequence of PPI photographs taken at 1-degree intervals of scanner elevation.
(3) The different analysts selected different storms on the photographs for 1630 IST on 16 May. No meaningful average is possible.

TABLE II—PARCEL-THEORY HEIGHTS OF STORM TOPS Z_p, CALCULATED USING DIFFERENT TECHNIQUES

Date	Manual tephigram construction	Roach & James's original program		Roach & James's program modified to use regional mean surface data lifted by 30 mb		Highest agreed measured storm top, Z_s	Updraught at level Z_e from Roach & James's modified program
(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)
	1730 IST	0530 IST	1730 IST	0530 IST	1730 IST		1730 IST m/s
12 May	61	57	53	63	63	64	68
13 May	65	<50	53	63	>65	—	97
16 May	67	63	>65	63	63	62	78
17 May	64	>65	63	>65	63	60	92
19 May	63	63	63	>65	63	60	86
20 May	67	57	63	63	>65	—	95
21 May	69	63	>65	>65	>65	61	104
22 May	68	63	57	>65	>65	65	106
23 May	61	57	63	63	63	61	66
28 May	64	63	57	63	63	61	83
30 May	65	<50	57	63	>65	37	95
31 May	62	57	57	63	63	58	68
1 June	65	<50	57	>65	63	65	77
2 June	67	<50	57	63	63	58	86
3 June	67	57	63	>65	>65	60	99

In columns (ii) and (vii) heights are given in thousands of feet.

In columns (iii), (iv), (v) and (vi) heights are indicated according to the following code:

<50	Z_p < 50 000 ft (15·2 km)
53	50 000 ft < Z_p < 55 000 ft (16·7 km)
57	55 000 ft < Z_p < 60 000 ft (18·2 km)
63	60 000 ft < Z_p < 65 000 ft (19·8 km)
>65	65 000 ft < Z_p

height of 60 000 ft (18 km). No tops above 60 000 ft (or nearer to Z_p than 4000 ft below it) subsequently rose.

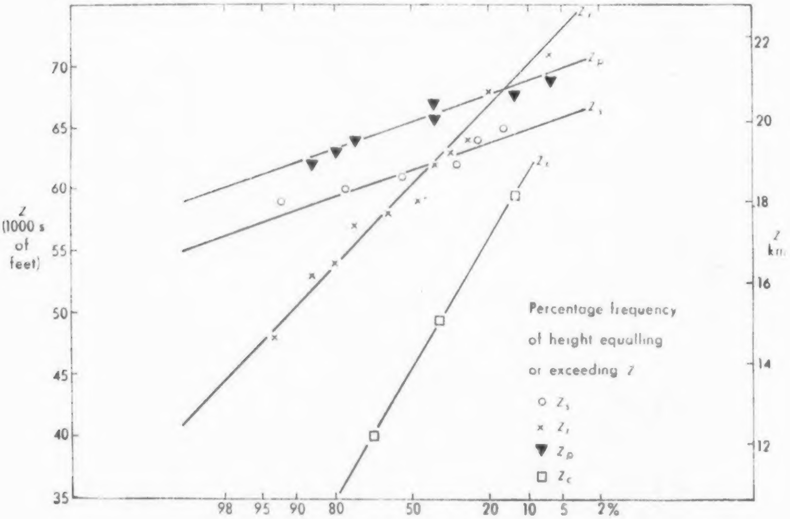

FIGURE 2—RELATIVE FREQUENCY OF TOPS EXCEEDING SPECIFIED HEIGHTS

Z_s is the highest agreed measured storm top for each of the 13 days of flights (see col. (vii) of Table II).
Z_p is the parcel-theory storm top for days of flights, found by hand.
Z_r is the highest echo top measured with the airborne radar on days of flights.
Z_c is the climatological highest daily echo top for May from ground-based radar data due to Rakshit.

Measurements made from the ground. The heights of the tops of some storms were measured from the ground using the 31-mm radar at Dum Dum Airport. (The characteristics of this radar are listed in Appendix I). The measurements are listed in column 9 of Table I. Those marked with a single asterisk were measured by the technique used as routine at Dum Dum. Those marked with two asterisks were estimated using PPI photographs at one-degree intervals of scanner elevation. Mostly, the tops are lower than the radar tops measured from the air. In 16 of the 20 measurements the storm was 200 km or more from Dum Dum, so that accurate height finding by the radar might not be expected. On 31 May, though, storm M_2 was only 30 to 40 km away so that the measurement of 40 000 ft at 1530 IST might have been expected to be accurate. Measurements from the air show a growth of the radar echo top from 54 000 ft at 1521 to 63 000 ft at 1540 IST. Allowing for half-beam-width corrections and other effects, the lowest likely air measurement for 1521 would be 47 000 ft and for 1540 IST 56 000 ft. The measurements from the ground and the air are not synchronous, however, and it is possible that the top may have subsided between 1521 and 1530 IST. Photographs of the visible cloud show that it was developing into its mature

stage and it seems much more likely that synchronous observations would have shown a discrepancy between the ground and air observations of between 10 000 and 20 000 ft. Such discrepancies are not understood, especially as measurements of the height of the survey aircraft using both PPI and RHI gave differences not exceeding 1 km (3300 ft) at ranges up to 100 km and at aircraft heights of up to 5 km (16 500 ft). No storm had its top underestimated because of attenuation by other storms intervening between it and the ground radar.

Overall it must be concluded that the agreement between the ground and airborne radar observations is poor. The reason is not known.

Comparison of the measured storm tops with heights given by some commonly used techniques. The measurements were made primarily to provide information for aviators. From one planning point of view it is enough that the occurrence of storms at certain heights should be established beyond doubt. From another, extrapolation from the measurements towards a climatology of storm tops is desirable. Because of the way in which the storms were necessarily chosen, the present data cannot be used in a statistically meaningful way. However, the possibility of deriving a climatology indirectly is discussed later. Another aviation requirement, though, is for assessments of the likelihood of tops exceeding certain levels on a particular flight in the near future. Since such forecasts would be based on data available as routine to the forecaster, the measurements of visible tops have been compared with three quantities derived from routine radio-soundings (see columns 10, 11 and 12 of Table I).

The tropopause (column 12) was penetrated by storms on every flight (except flight 15 on 30 May, when there was comparatively little convective activity). The level Z_e (column 11) was similarly exceeded. This is the equilibrium level of the so-called 'parcel theory'[10,16] at which buoyancy is reduced to zero (see Figure 3). In the United Kingdom it is often used as a guide to the height of the tallest air-mass convective clouds. In parcel theory, where no entrainment is envisaged however, Z_e is the level of maximum updraught. To calculate Z_e, the tropopause height and the updraughts at Z_e (also listed for convenience in Table II), the sounding at 1730 IST from Dum Dum was used. A temperature representing the air near the ground during the afternoon was found from the mean of the maximum temperatures measured at the six stations shown in Figure 1. A representative humidity mixing ratio was found from the dew-points reported by these stations at 1730 IST. In making the tephigram constructions it was found that these regional temperatures and humidities sometimes would have failed to release convection. As deep convection usually starts over the hills and a comparison of average daily maximum temperatures at Ranchi (652 m), Jamshedpur (131 m) and Asansol (126 m) in May and June showed that surface temperatures there fall with height at less than half the dry adiabatic lapse rate, it seemed appropriate to use the regional temperatures at a lower surface pressure. It was found that by attributing them and the regional humidities to a pressure 30 mb less than that at Dum Dum convection was always released. It is noteworthy that the sounding for 0530 IST gave a similar Z_e (and Z_p) on all occasions except one where a major change occurred between 0530 and 1730 IST.

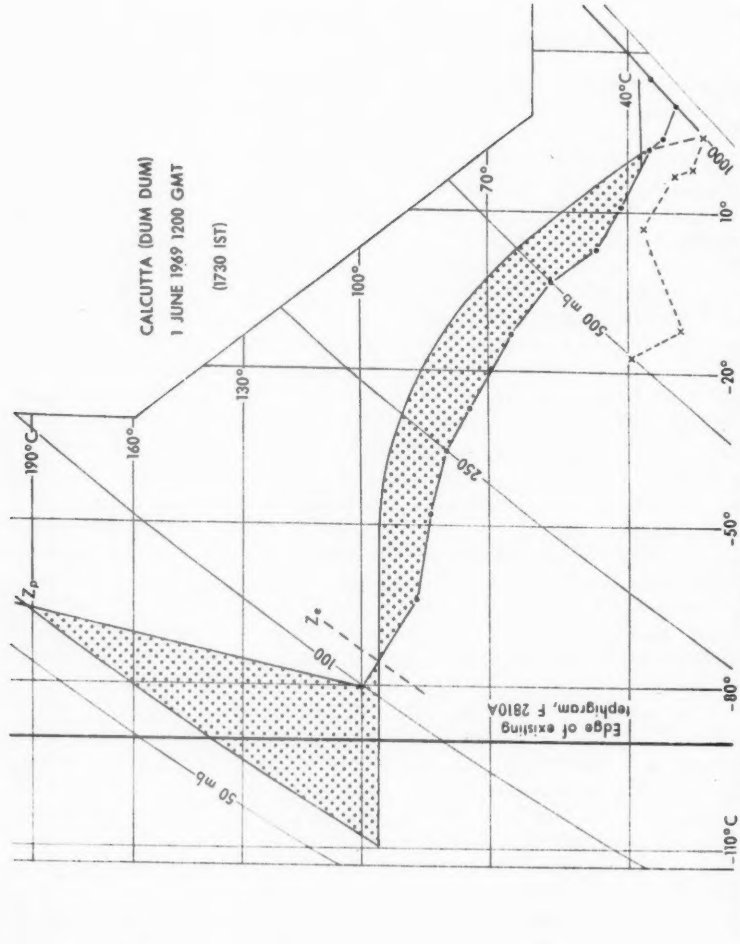

FIGURE 3—SCHEMATIC TEPHIGRAM FOR THE AFTERNOON WHEN STORM S_2 WAS MEASURED ON FLIGHT 17
Environment and ascent curves are shown. Z_e and Z_p are the parcel-theory equilibrium and storm top levels.

The tephigram was also used to estimate the parcel-theory top of the storm Z_p (see Figure 3). This was found to be nearer the heights of the highest tops observed each day than Z_e or the tropopause; if the measurements of visible tops on which all three analysts did not agree are eliminated, then on only 1 occasion out of 13 was Z_p exceeded (by 3000 ft). On 11 of these occasions the highest top rose to within 9000 ft of Z_p. In this set of data, however, there is no significant statistical correlation between the highest observed top on a given day, Z_s, and Z_p for that day. Perhaps none should be expected because of the narrow spread in both quantities and the way the clouds were selected. Although the pilot would probably choose the highest storm he could see, it is unlikely that he could choose to study the storm that was destined to be the tallest that afternoon and even less likely that he would work on it when it was at its tallest. On the other hand this comment would be less valid if many storms reached the same highest level, as Ludlam and Saunders[17] found with cumulus in Sweden.

Before each flight the pilot received a forecast for his general area of operations which in most cases included a statement of the expected heights of the highest cumulonimbus tops. These heights are listed in column 13 of Table I. The high tops that were measured were clearly not expected. In passing it may be noted that neither the tephigram used at Dum Dum Airport nor any in use in the U.K. Meteorological Office would have allowed forecasters to make the construction to find full parcel-theory tops for these occasions without an extension of the diagram.

Use of Z_p to assess the probability of high tops. Roach and James[18] have used radio-soundings from selected parts of the world to calculate the proportions of occasions on which Z_p falls in selected height bands in different months of the year. For the initial state of the buoyant parcel they used surface temperature and humidity data at the sounding station. They gave some weight to temperature and humidity at 850 mb and ignored any negative area at low levels which would have inhibited convection from the ground altogether. At all times of year storms in this area (apart from cyclones) are locally convective and so Roach and James's computer program has been modified to use for the initial state of the parcel the regional mean afternoon temperatures and humidities referred to in the previous section. Applied to air with a pressure 30 mb less than that at Dum Dum these values lead to the distribution of Z_p shown in Figure 4. From a comparison with Z_p for the days of flights, it can be seen that observations were made on days whose median Z_p is 9000–11 000 ft (3 km) higher than at Calcutta for May and June in 1961–66*. Flights were made on 15 days or 15/61 ($\approx\frac{1}{4}$) of the days in May and June. Z_p for this one-quarter of a May and June exceeded 62 000 ft, and it can be seen that the top one-quarter of the climatological curves also exceeds that height. The coincidence is notable and implies

**Note.* This comparison is worth less than one would wish because a new type of radiosonde was used from 1 May 1968. The new sonde allocates temperatures to higher pressures than did the one used in 1961–66. Fortunately Z_p is insensitive to this change as it depends on both the tropospheric lapse and the stratospheric inversion. A comparison of some monthly mean soundings showed that the monthly mean Z_p (based on ascent beginning at 850 mb with zero buoyancy) did not vary systematically with the introduction of the new sonde. Insufficient data from the new sonde are readily available to permit a longer-period comparison. No correction for the change in sondes has been made.

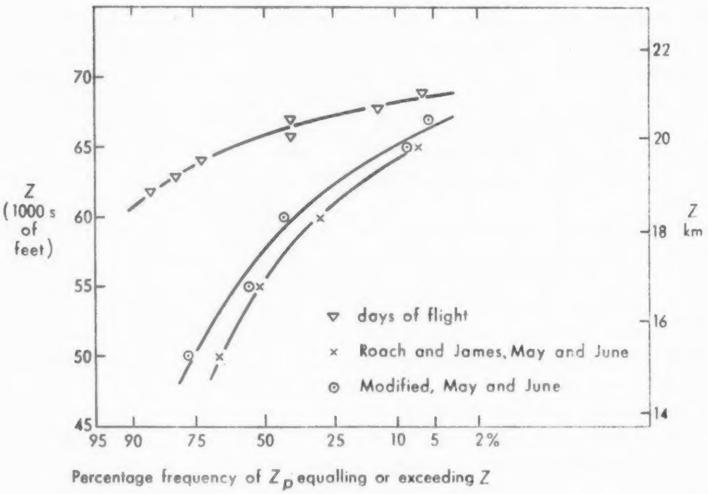

FIGURE 4—RELATIVE FREQUENCY OF Z_p EXCEEDING SPECIFIED HEIGHTS

Days of flights are compared with mean values for May and June 1961–66.

either a remarkable choice of days on which to fly in a normal year or an abnormal year with Z_p higher on the whole than in 1961–66. Days for flying were indeed chosen to be days of tall storms but it is likely that Z_p was higher in May and June 1969 than the average for 1961–66.

A day-by-day comparison of Z_p, made by using a planimeter to equate the positive and negative areas on a tephigram, by using Roach and James's original computer program, and by using the modified program, is given in Table II. Except in a few marginal cases the agreement between the manual construction and the modified program (columns (ii) and (vi)) is good.

A comparison of the manually calculated Z_p for days of flights with the Z_s for those days is also shown in Figure 2. Both sets of measurements fit a normal distribution quite well. The mean (and median) Z_s lies 4000 ft (1·2 km) below the mean Z_p but a pair of parallel lines fits both arrays of points quite well so that they have similar standard deviations (2600 ft). In Appendix III it is suggested that Z_s may have been systematically underestimated by 2000–4000 feet. If this is truly so then the agreement between the distributions of Z_s and Z_p is good indeed. Of course the present results are based on a small sample and more general agreement should not be assumed; nevertheless the agreement found between Z_s and Z_p, and that of Z_p found manually with Z_p found using Roach and James's modified computer program encourage extension of Roach and James's work on Z_p to find seasonal values of the daily maximum storm height in other tropical areas.

Comparison with earlier radar climatologies of the area. Bhattacharyya and De[15] have analysed routine hourly observations of the heights of cumulonimbus tops made with the radar at Dum Dum, the characteristics of which are listed in Appendix I. Their analysis covered the pre-monsoon and monsoon seasons of 1959 to 1962. Rakshit in a paper to be

published (private communication) has extended the analysis to include 1963 and 1964. He found higher frequencies of high tops in the pre-monsoon season than Bhattacharyya and De. He also found that the highest top each day was more often above 15 km and 18 km in May than in any other calendar month. His results for May are shown as Z_c on Figure 2. The frequency of high tops from this radar climatology is much less than was found during the flights of this investigation. The number of flights is, of course, small and flights were made on days when the forecasters expected tall storms. However, even if one assumes that on the 23 days between 12 May and 3 June 1969 storms above 50 000 ft (15 km) occurred only on the 13 days when the aircraft made optical measurements, high tops were still more frequent than in the radar climatology. A comparison of columns 4 to 8 of Table I with column 9 suggests that the ground-based radar observations were often underestimates and that therefore the summaries of similar observations should be regarded as frequencies which can be expected to be exceeded.

Conclusions. There is little doubt that storms with tops exceeding 60 000 ft (18 km) occurred on most days when measurements were made. On some days tops reached at least to 65 000 ft and probably to around 68 000 ft. One storm top at 60 000 ft was rising at 1200 ft/min (6 m/s).

Because the storms which were measured were, for good practical reasons, chosen neither systematically nor entirely randomly, no conclusions may be drawn about the relative frequencies of tops exceeding specified levels. However, the measurements indicate that high tops were more frequent in May and early June 1969 than in the existing summaries of ground-based radar measurements. Although Z_p was higher during the flights than during 1961–66 it still seems very likely that the existing radar summaries for Calcutta will underestimate the frequency of high tops at all times of the year.

Although there was little agreement between the day-to-day variations in the heights of storm tops, Z_s, and the parcel-theory tops, Z_p, nevertheless Z_p was a better indicator (and predictor) of Z_s than either the equilibrium level Z_e, the tropopause or the heights given in the forecasts issued for the flights. Agreement was best between Z_s and the mean value of Z_p over the days when flights were made.

Acknowledgements. Most of the data were obtained and reduced by Fairey Surveys Limited for the Royal Aircraft Establishment, Bedford. It is a pleasure to acknowledge the persistence, integrity and professionalism of Mr F. Worton, Captain G. Milsom and the crew of G-AHCT.

The India Meteorological Department co-operated fully in providing a variety of meteorological facilities as well as the use of its 31-mm radar at Dum Dum. Mr U. R. Acharya, Officer-in-charge of the meteorological office at Dum Dum Airport, and his staff could not have been more helpful. Mr D. K. Rakshit and his team operated the radar with skill and enthusiasm.

Professor F. H. Ludlam acted as third analyst. His contribution in making available his wide experience of observing clouds was invaluable. Mr K. Weston (also of Imperial College, Department of Meteorology) took an active part in obtaining and interpreting the ground radar measurements of storms being worked on from the aircraft.

Mr M. H. Freeman has contributed advice and constructive criticism of the manuscript.

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APPENDIX I—CHARACTERISTICS OF THE RADARS USED

Characteristic	Airborne radar	Radar at Dum Dum Airport
Type	Ecko 290	JRC NMD–451A
Wavelength	31 mm (9375±3 MHz)	31 mm (9345–9405 MHz)
Pulse duration	4 μs	1 μs
Pulse repetition frequency	400 pulses per second	300 pulses per second
Peak power	30 kW	>225 kW
Beam width (to ½ power)	3°	1·2°
Beam	Conical	Conical
Sidelobes	No information No effects observed	25 dB down at 2° Second lobe at 4°
Iso-echo inversion	12 dB above minimum detectable signal	None
Display	Plan position indicator	Range–elevation, range–height and plan position indicators
Max. displayed range	50 nautical miles	540 km in a chosen direction, 300 km all round.

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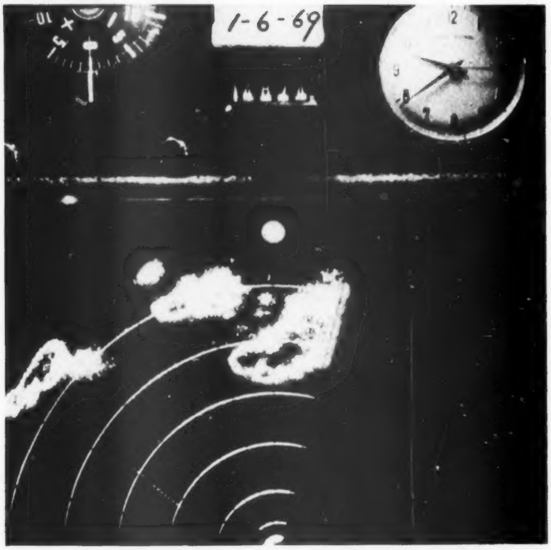
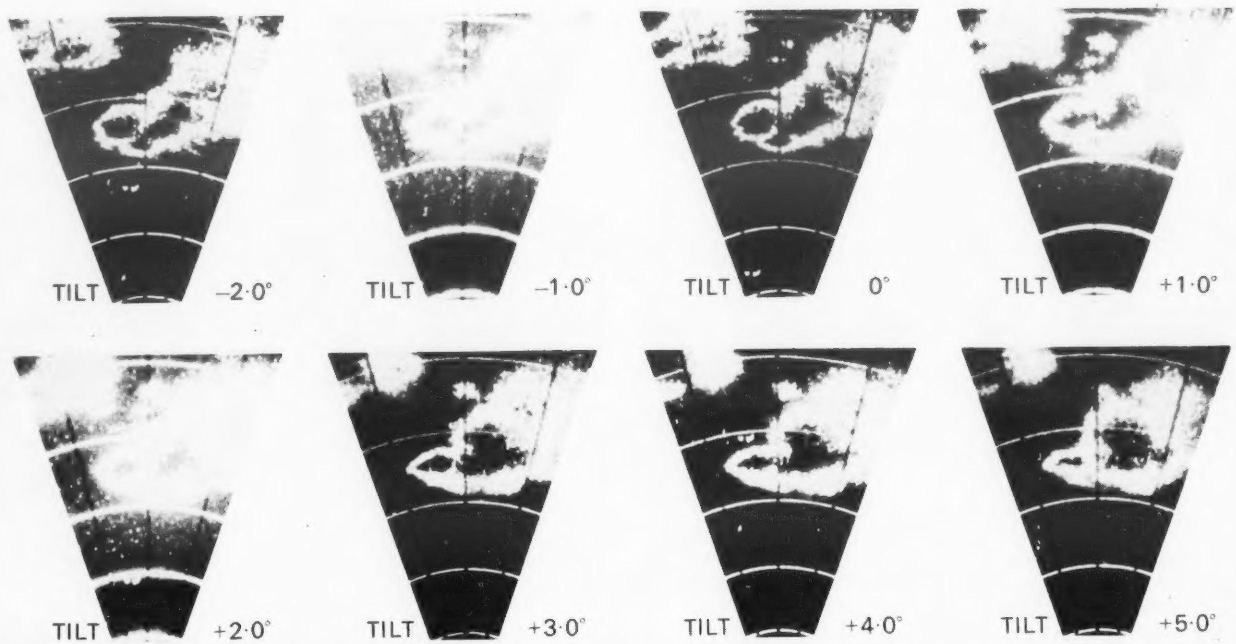


PLATE I—SIMULTANEOUS CLOUD AND RADAR PHOTOGRAPHS OF THE 65 000-ft (19·5-km) TOP OF STORM S_2 AT THE BEGINNING OF RUN 5, FLIGHT 17

Note the cirrus above the storm top. Time is GMT (=IST $-5\frac{1}{2}$ hours).



TILT −2·0°
TILT −1·0°
TILT 0°
TILT +1·0°
TILT +2·0°
TILT +3·0°
TILT +4·0°
TILT +5·0°

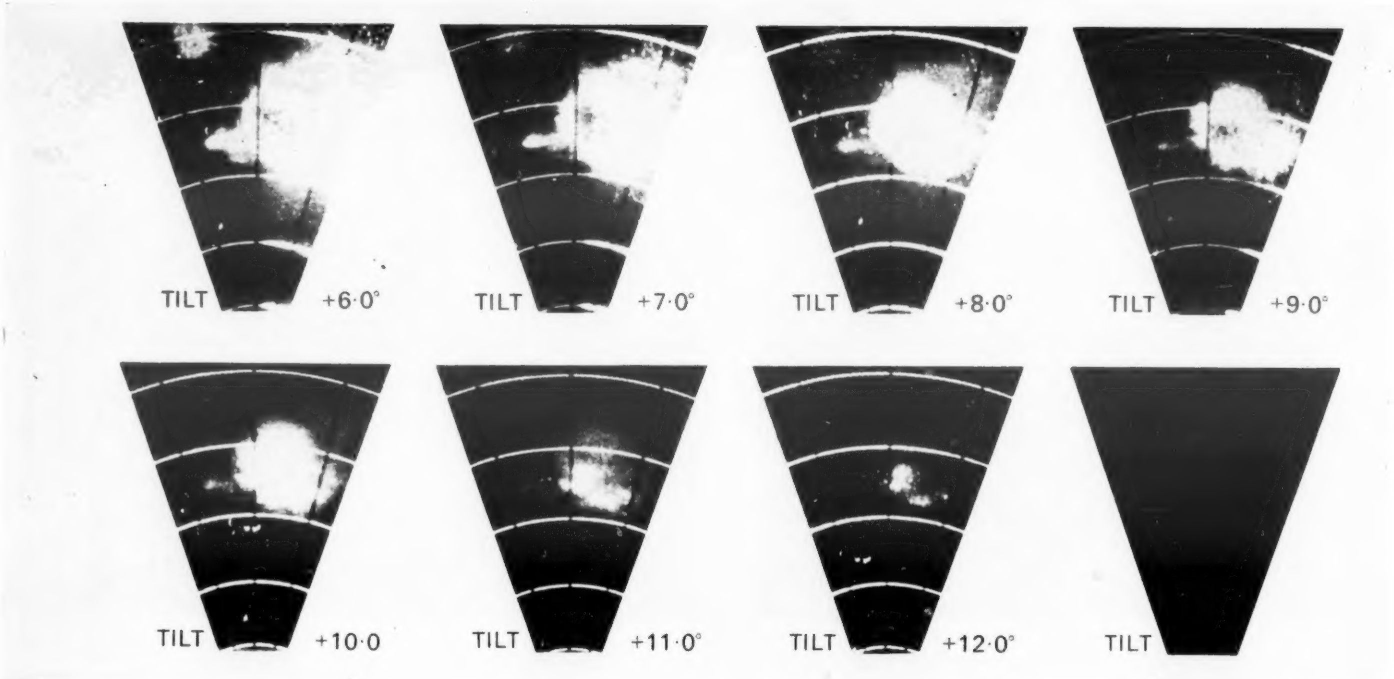


PLATE II—RADAR RETURNS OBTAINED WITH THE SCANNER RAISED BY 1-DEGREE STEPS, RUN 5, FLIGHT 17

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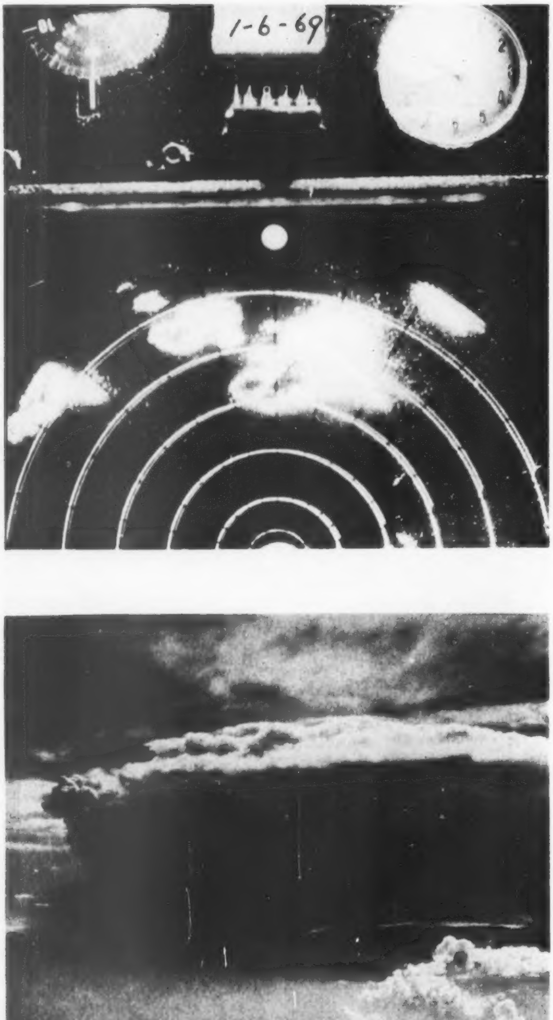

PLATE III—SIMULTANEOUS CLOUD AND RADAR PHOTOGRAPHS OF STORM S_2 AT THE END OF RUN 5, FLIGHT 17

Note also the velum at the storm top. Time is GMT (=IST $-5\frac{1}{2}$ hours).

APPENDIX II—METHOD FOR DETERMINING THE HEIGHTS OF STORM TOPS

(a) The height h_2 of the top of a visible cloud was derived from :

$$h_2 = h_1 + \nu + \frac{Dh}{fe} + C_\theta + C_\varphi + C_R,$$

where h_1 = height indicated by the aircraft's ICAO-atmosphere calibrated pressure altimeter set to 1013·2 mb;

ν = a correction calculated from the afternoon radio-sounding from Dum Dum ($h_1 + \nu$ represents the geometrical height of the aircraft above MSL);

D = radar range of the centre of the radar return from below the cloud top, when the radar scanner was horizontal. (D represents the distance between the camera lens and the vertical through the cloud top, measured along the horizontal axis through the camera);

f = focal length of the camera;

e = a factor to allow for enlargement of the photographs ($\times 2$ was used);

h = distance measured on the cloud photograph from the horizontal centre line to the top of the cloud;

C_θ = a term to correct for the aircraft's (strictly the camera's) pitch attitude, θ, ($C_\theta = D \tan \theta$);

C_φ = a term to correct for the aircraft's (strictly the camera's) roll attitude, φ. ($C_\varphi = \frac{D}{fe} (d \tan \varphi + h [\sec \varphi - 1])$). As φ was always small the term $h [\sec \varphi - 1]$ was neglected;

d = distance measured on the photograph from the vertical centre line of the photograph to the vertical through the cloud top;

C_R = a term to correct for effects of the earth's curvature. ($C_R = R (\sec \alpha - 1) + D \sin \beta (\sec [\alpha + \beta] - \sec \beta)$);

R = vertical distance between the camera and the centre of the earth. (R was taken as 6381 km);

$$\alpha = \tan^{-1} \frac{D}{R};$$

$$\beta = \tan^{-1} \frac{h}{f}.$$

(b) In principle the height h_2' of the top of the precipitation returning a radar signal was derived from

$$h_2' = h_1 + \nu + D_e' \sin \beta_e + C_R',$$

where D_e' = slant range of the radar return from the top of the storm;

β_e = tilt angle of the radar scanner when pointing at the top of the storm;

C_R' = a term to correct for effects of the earth's curvature; ($C_R' = R [\sec \alpha - 1] + D \sin \beta [\sec (\alpha + \beta_e) - \sec \beta_e]$);

As the radar scanner was gyroscopically stabilized no corrections were needed for aircraft attitude. Because of the large errors in β_c discussed in Appendix III and also because it was found that the corrections ν and C_R' tended to cancel neither of the latter corrections was applied.

(c) The photographs and records of pitch and roll were measured twice by different analysts and two independent sets of results were obtained for

$\left(\dfrac{Dh}{fe} + C_\theta + C_\varphi\right)$ and for $D_c' \sin \beta_c$.

The terms $(h_1 + \nu)$ and C_R were evaluated only once for each run. The heights given in columns 4, 5 and 6 of Table I are means of the two assessments.

APPENDIX III—THE ERRORS IN MEASURING STORM TOP HEIGHTS

In this appendix the notation is that used in Appendix II.

The likely standard error of a measurement of indicated height on a pressure altimeter, h_1, is about 100 ft (30 m) and of ν about the same. The combined error in the aircraft's geometric height $(h_1 + \nu)$ is therefore about 150 ft (45 m).

The random error in the major term (Dh/fe) may be gauged from the standard deviation of the differences between values found by the first two analysts. The range D and the distance h were each measured twice. Together they contribute almost all the standard error of 2100 ft in (Dh/fe) shown in Table III. A systematic error in D will have arisen from attenuation of the 31-mm radar beam. Attenuation will have produced an apparent shift of the centre of strong echoes towards the radar. The effect cannot be assessed quantitatively but may perhaps amount to a mile or two. If it does (Dh/fe) is underestimated by 5 to 10 per cent. For some of the highest tops this could be equivalent to a systematic underestimate of 2000 to 4000 feet. This has not been allowed for. In particular cases it could be cancelled out by the random leaning of the cloud towers. The focal length f was measured precisely at RAE Farnborough and may be taken as effectively exact. The enlargement factor, e, is known to within 0·2 per cent. Its contribution to the error is therefore about 80 ft.

TABLE III—ERRORS ARISING FROM DIFFERENT TERMS USED IN EVALUATING VISIBLE STORM TOPS

Term (see Appendix II)	Systematic error *feet*	Random error *feet*
h_1	0	±100
ν	0	±100
Dh/fe	−2000 to −4000 (say −3000)	±2100
C_θ	±300	±315
C_φ	±50	±220
C_R	0	±30

The likely standard error of a visible top in Columns 4 and 5 of Table I is −3000 ±1500 feet (−900 m ±450 m). Each entry in columns 4 and 5 is the mean of two assessments. This error excludes cases where there is a gross difference in interpretation between columns 4 and 5 and Ludlam's values in columns 7 and 8.

The pitch attitude, θ, was also always measured twice.

Table III gives the error in reading θ from the recorder film. The unknown systematic error in the instrumental system for determining θ is considered to be less than 1/10 degree and the random instrumental error is about the same.

Similarly, the roll angle φ and displacement d were measured twice. The reading error due to roll is 220 ft while the unknown systematic instrumental error is thought to be less than 1/5 degree, equivalent to about 50 ft in most cases. Random instrumental effects have been assessed as giving an additional error which is less than half that due to reading errors.

The correction for the earth's curvature C_R was tabulated to the nearest foot but interpolation may have led to errors of about 30 ft. The correction ranged from + 225 to + 1700 ft with a mean value of 870 ft.

Refraction of the radar beam in a spherically curved atmosphere causes the higher radar tops to be systematically underestimated by about 200 ft. In deriving this figure, a temperature and humidity variation with height was used, which was the mean for the days on which flights took place. The day-to-day differences in the effects of refraction were not examined but are likely to be less than this, equivalent, say, to a random error of 100 ft.

The effects of errors in R are entirely negligible.

The slant range D_c' was always measured twice (see Table III). The attenuation, which introduced errors in D, does not do so here.

The highest scanner angle at which a radar return was recorded β_c was effectively decided by the instrumentation operator in the aircraft. It has two main sources of error. The first concerns the glow left after each sweep of the radar and the second the width of the radar beam. At times the operator took 15 to 20 photographs in about 100 seconds, raising the radar scanner by one degree between photographs. It seems likely that he was not always able to follow his instruction to allow the afterglow from one elevation angle to die before taking the photograph of the return obtained at the next higher angle. The afterglow would then be interpreted as echo obtained at the higher angle. Probably the afterglow would not have persisted after two photographs, i.e. two degrees. Secondly, no correction was made to allow for a return being received when the cloud top was in the main lobe of the radar beam but below its axis. In some circumstances a half-beam-width correction is used to allow for this. These two effects mean that some elevation angles β_c may be up to $3\frac{1}{2}$ degrees too high. In comparison, the likely standard error due to errors in the stabilization system ($\pm 0{\cdot}1°$) is trivial. If β_c is reduced by $3\frac{1}{2}$ degrees, all the radar tops come below the visible tops.

None of these effects is so important as the interpretation of the photographs themselves. This may lead to large yet unassessable errors. The analyst must associate each cloud tower with a corresponding radar echo. Referring to the analyst's most common difficulty Professor F. H. Ludlam (private communication) has written 'When cloud tops have become surrounded by a shelf of anvil cloud it is difficult to be certain whether knobbly detail seen at the highest elevation in a photograph is the peak or nearer protuberances from the upper part of the anvil cloud. If such protuberances conceal the peak the calculated height may be an overestimate of several thousand feet. This kind of difficulty arises even at the up-shear side of the

storm, where the horizontal extension of the anvil cloud away from the peak is a minimum, but still reaches several miles in storms with very high tops'. He has termed this 'anvil interference' or AI. The effect of differences in interpretation is best seen by comparing Ludlam's re-assessment with the original measurements (see Table I).

Overall, 2000 to 4000 ft should probably be added to measured visible tops to allow for systematic errors. The combined random error for visible tops listed in columns 4 and 5 is ± 1500 ft.

The error in the measurements of radar tops because of errors in β_c is sometimes 10 000 ft, masking all other errors whether systematic or random.

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A SIMPLIFIED SNOW PREDICTOR

By B. J. BOOTH
(Meteorological Office, Upavon)

Summary. An earlier analysis of snow observations made at Upavon is reconsidered and a simplified snow index is suggested. A test of an American snow forecasting method is also briefly discussed.

Introduction. Some three years ago the present writer examined Upavon precipitation data to test the effectiveness of dew-point temperature as a snow predictor.[1] The *Air Weather Service Technical Report* No. 233[2] describes a snow forecasting method applicable to the area just east of the Rocky Mountains. Wet-bulb temperatures at the surface, T_W, and at 850 mb, $T_{W_{850}}$, are estimated from the relevant surface and upper-air observations. These are entered on Figure 1 and the type of precipitation to be expected is obtained. (Figure 1 is a modified version of the diagram described in the original article, in that it has only 4 areas as against 6 originally.)

The 00 and 12 GMT surface and 850-mb wet-bulb temperatures were estimated from the dry-bulb and dew-point temperatures (T, T_d) measured at Crawley/Gatwick, Stornoway and Gorleston/Hemsby, when precipitation was occurring during the five winters 1966/67–1970/71, winter being defined as the period from 1 November to 30 April. The data were extracted from the *Daily Weather Report*[3] and the *Daily Aerological Record*.[4] These observations were then entered on Figure 1 and the expected type of precipitation compared with that actually experienced. Table I summarizes the results obtained.

TABLE I—PERCENTAGE FREQUENCY OF CORRECT PRECIPITATION FORECASTS

	Freezing rain (A)	Snow (B)	Rain (D)
Non-showery precipitation	No occurrences	98 [44]	93 [124]
Showery precipitation	No occurrences	96 [73]	78 [108]

[ ] = Total number of precipitation occurrences in each area. Area C is not included since one would expect mixed types of precipitation in this area.

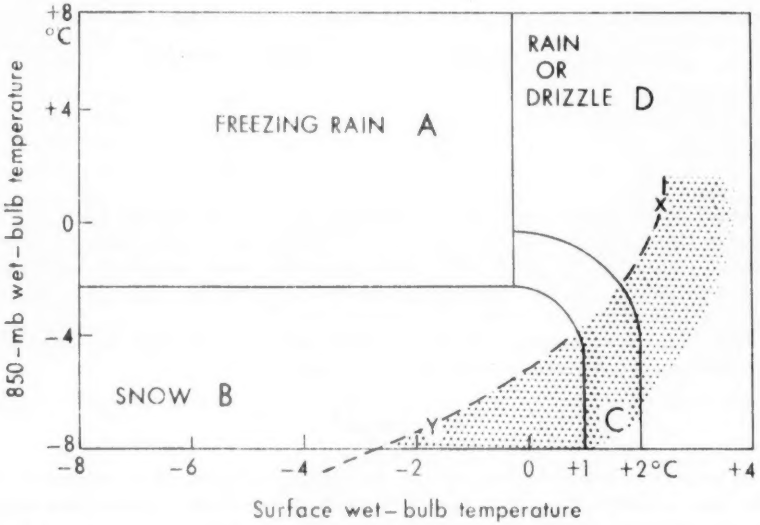

FIGURE 1—TYPE OF PRECIPITATION RELATED TO THE SURFACE AND 850-mb WET-BULB TEMPERATURES

C represents the occurrence of precipitation of mixed types.

While at first the method appears to give a high percentage of correct forecasts, further study of Figure 1 showed that over 98 per cent of all observations (461) fell within the shaded area. The line bounding this area, XY, intersects the boundary line of areas B and C at $T_W = 1$°C, i.e. nearly all precipitation observations were of snow when $T_W < 1$°C and of rain when $T_W \geqslant 1$°C. There is no similar value for $T_{W_{850}}$. In other words equally good results could have been obtained by referring to the surface wet-bulb temperature alone (at least over the British Isles).

This T_W value of 1°C appears to be the critical temperature at which precipitation may or may not be in the form of snow and is in good agreement with an idea described by Booth.[1]

Discussion. In an earlier article Booth[1] suggested that if precipitation was occurring and the dew-point depression $\leqslant((-2 \times T_d) + 1)$ degC, then there was a good chance that the precipitation would be in the form of snow. This is rather a cumbersome equation to remember, especially since the original idea was to obtain a simple, readily calculated index which could be plotted and followed on synoptic charts.

The original Upavon data have now been reanalysed and a simpler form of a snow index, I_s, obtained by adding together the surface dew-point and dry-bulb temperatures on occasions when precipitation was occurring. Table II shows the frequency of non-showery snow for various values of I_s. ($I_s = T + T_d$.)

TABLE II—PERCENTAGE FREQUENCY OF NON-SHOWERY SNOW AT UPAVON

I_s	*percentage frequency*	*number of observations*
−3	100	24
−2	96	46
−1	91	65
0	79	82
1	47	34
2	17	59

This suggests that a value of I_s between 0 and 1 is the critical value which separates precipitation in the form of rain from that in the form of snow. This is supported by Table III which uses data from Gatwick, Gorleston and Stornoway. If one considers showery precipitation then the critical value of I_s lies between 2 and 3 (Tables IV and V).

This index is a function of the wet-bulb temperature since for dry-bulb and dew-point temperature between $+ 7°C$ and $- 7°C$

$$T_W \approx \frac{T + T_d}{2}.$$

In using the index to forecast the probability of snow, it is necessary to take into account the cooling effect of melting snowflakes. Rain may turn to rain and snow mixed (sleet), then to snow, even though the value of I_s is somewhat greater than 1 before precipitation starts. Lumb[5,6] has shown that the highest wet-bulb temperature at which instability rain can turn to snow is 3·5°C, whilst for prolonged frontal precipitation the value is 2·5°C. The sums of the dry-bulb and dew-point temperatures, as plotted on a synoptic chart, which give wet-bulb temperatures of this magnitude are 6 or 7 and 5 or 6 respectively. Thus if $I_s \leqslant 7$ and precipitation commences as rain then there is a possibility that the rain could turn to snow.

TABLE III—PERCENTAGE FREQUENCY OF NON-SHOWERY SNOW AT GATWICK, GORLESTON AND STORNOWAY

I_s	*percentage frequency*	*number of observations*
−3	100	4
−2	100	6
−1	88	8
0	65	17
1	30	10
2	32	19

TABLE IV—PERCENTAGE FREQUENCY OF SHOWERY SNOW AT UPAVON

I_s	*percentage frequency*	*number of observations*
−3	100	1
−2	100	4
−1	100	2
0	80	5
1	88	8
2	67	3
3	25	8
4	33	9

Although the height of the 0°C wet-bulb level above ground level is of great importance in snow forecasting, as Lumb[7] has demonstrated, its use has one major drawback — namely that of trying to decide which upper-air sounding is representative of a station or area, and how it will change in the

future. On most occasions of rain changing to sleet or snow it is reasonable to expect that the downward penetration of colder air will produce a lapse rate from the surface up to 600 m (the greatest depth through which snow can be expected to penetrate downwards), which is near to the saturated adiabatic. This has been confirmed by a study of 90 occasions of rain or sleet with surface temperatures near 0°C during February 1972. Figure 2 shows the relationship obtained between the height of the wet-bulb freezing level, H, and I_s. A similar relationship was obtained when 12 GMT values of I_s and H were calculated for 111 occasions when no precipitation was occurring. It follows that the use of the index I_s will give an indication of the area where the height of the 0°C wet-bulb temperature is lowest and movements of the isopleths of I_s will reflect temperature changes due to advection or vertical penetration of colder air.

TABLE V—PERCENTAGE FREQUENCY OF SHOWERY SNOW AT GATWICK, GORLESTON AND STORNOWAY

I_s	*percentage frequency*	*number of observations*
−3	100	6
−2	83	6
−1	86	14
0	100	24
1	85	13
2	73	26
3	44	18
4	43	23

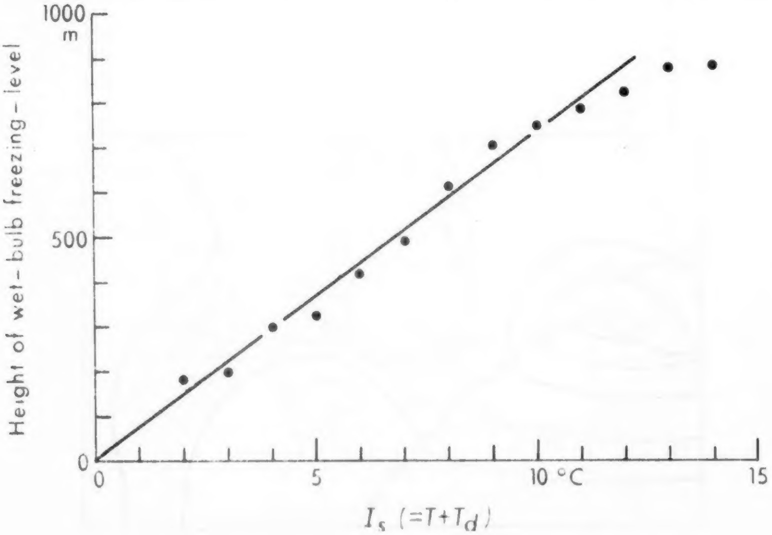

FIGURE 2—RELATIONSHIP BETWEEN SNOW INDEX I_s AND HEIGHT OF THE WET-BULB FREEZING LEVEL

Examples of the use of I_s. The following three examples illustrate the use of the isopleths of I_s in assessing the probability of snow or rain changing to snow.

Snowfall over England on 11–12 *February* 1970. Figure 3 shows the synoptic situation at 12 GMT on 11 February 1970 and the track of the depression during the next 24 hours. Precipitation in the form of rain reached south-western counties during the late afternoon of 11 February and spread quickly east and north. Most southern counties east of Cornwall and Devon experienced a short period of rain or sleet which quickly turned to snow. Farther north precipitation was solely of snow. Precipitation amounts of 15 mm were recorded at many places in southern England and at Plymouth a total in excess of 30 mm was noted.

The I_s pattern at 12 GMT on 11 February is shown in Figure 4. The low values in the London area are partly due to overnight stratus, the late clearance of which delayed the normal diurnal temperature rise. An I_s value nearer 3 or 4 would probably be more representative. As the depression deepened and moved along the English Channel the winds over Cornwall and Devon backed from south through east then north. With the onset of northerly winds cold air was advected over these counties and even here sleet was experienced. Prior to the advection of the colder air over the south-west peninsula all the sleet or snow reported fell over an area where the initial I_s was less than 7°C.

Figure 5 shows the boundary of the rain and snow ahead of the depression, together with the $I_s = 7$ isopleth at 12 GMT on 11 February 1970. By 12 GMT on 12 February all the south-western counties had an I_s value of 5 or less.

The polar air depressions of 25–26 *April* 1950 *and* 13–14 *December* 1958. These depressions have already been discussed in detail by Lumb[6] in terms of the

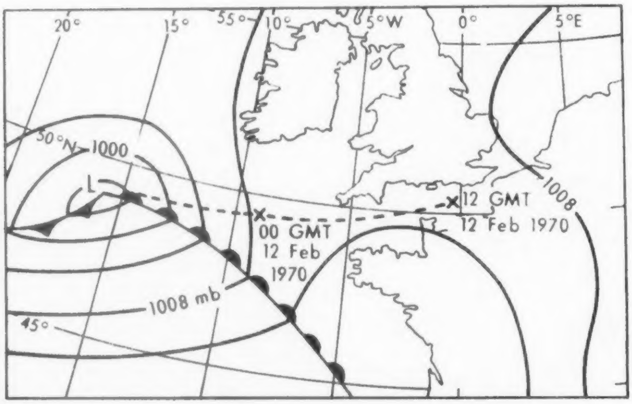

FIGURE 3—SYNOPTIC SITUATION AT 12 GMT, 11 FEBRUARY 1970

The track of the depression during the next 24 hours is also shown.

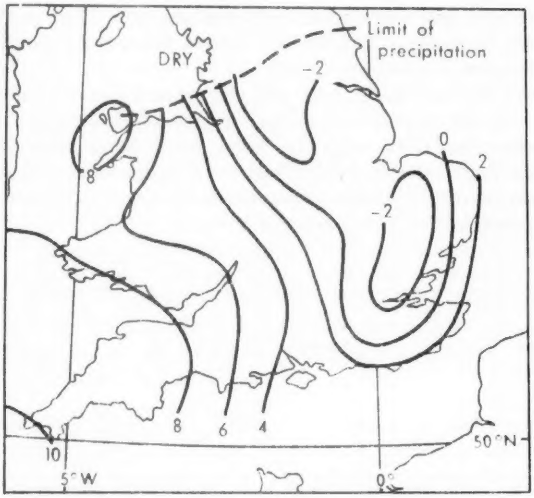

FIGURE 4—PATTERN OF SNOW INDEX I_s AT 12 GMT, 11 FEBRUARY 1970

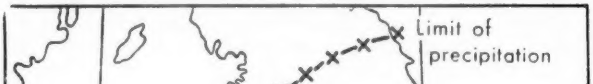

FIGURE 5—AREAS OF RAIN AND SNOW AHEAD OF THE DEPRESSION OF 11–12 FEBRUARY 1970

The I_s isopleth refers to 12 GMT, 11 February.

wet-bulb lapse rate and surface wet-bulb temperature. The purpose of these notes is to show in terms of I_s why rain turned to snow on the first occasion, but not on the second occasion.

The tracks of the two polar lows are shown in Figure 6. Figure 7 shows the isopleths of I_s for 12 GMT on 25 April 1950 and also the northern limit of the precipitation associated with the polar low; other than Cornwall and Devon most of England and Wales had an I_s value of less than 7. Within the area shown there was extensive moderate or heavy precipitation with up to 25 mm of precipitation being recorded.

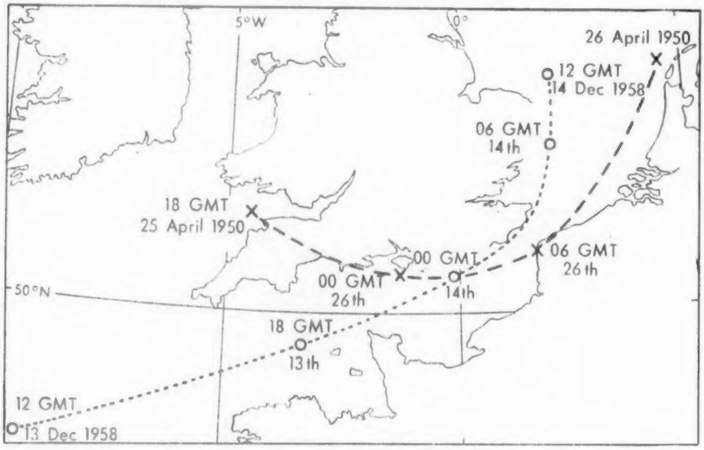

FIGURE 6—TRACKS OF TWO POLAR LOWS

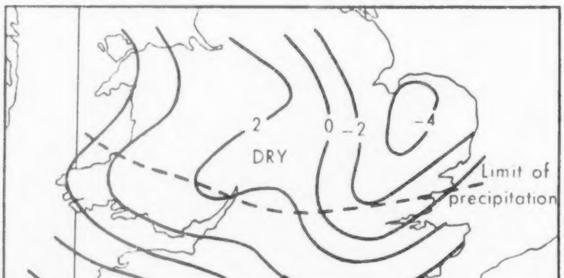

FIGURE 7—PATTERN OF SNOW INDEX I_s AT 12 GMT, 25 APRIL 1950

Precipitation commenced along the Welsh coast during the early afternoon and quickly spread east. Over Devon and Cornwall precipitation was in the form of rain, but elsewhere rain quickly turned to snow. Figure 8 shows the areas in which rain and sleet or snow was reported. It will be noted that the boundary between the rain and snow lies close to the $I_s = 7$ isopleth.

Figure 9 shows the I_s pattern at 12 GMT on 13 December 1958, together with the precipitation area associated with the polar low which moved north-eastwards along the English Channel. On this occasion precipitations fell into a régime in which the I_s value during the previous afternoon was in excess of 7, and hence only rain was reported. Had the air over the Midlands been colder and drier the rain would probably have turned to sleet as the surface winds backed through north behind the depression and advected cold air southwards. In fact, sleet was reported for a short while at London/Heathrow Airport as the surface wind backed to north-west. Heathrow lay on the northern edge of the rain belt.

Conclusion. An important element in trying to determine the form precipitation will take is T_W. Since T_W is not included in the synoptic code a simple function of T_W in the form I_s can be calculated from the reported T and T_d. If values of I_s are then plotted on surface charts the most likely areas of rain, snow or rain turning to snow will be indicated.

If the precipitation is expected to be of light intensity it will most likely be of rain if $I_s \geqslant 2$ and of snow if $I_s \leqslant 0$, but if continuous moderate or heavy precipitation is expected then rain could turn to snow over ground where the initial $I_s \leqslant 7$, provided that there is no warm advection at or near the surface. Rain may also turn to snow over areas into which colder air with $I_s \leqslant 7$ is advected.

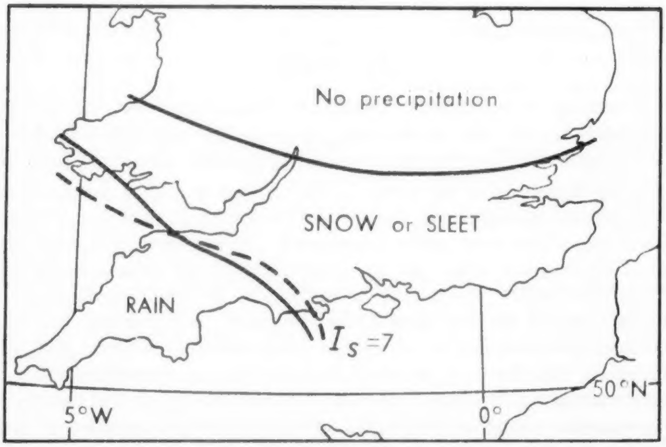

FIGURE 8—AREAS OF RAIN OR SNOW 25–26 APRIL 1950

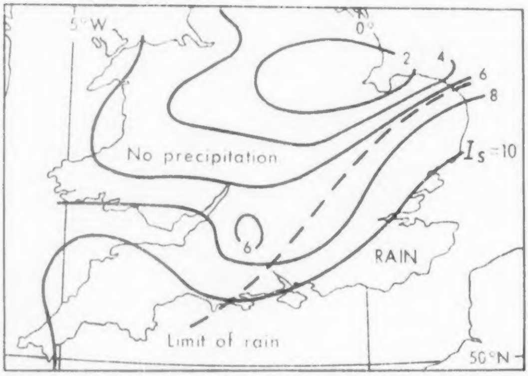

FIGURE 9—PATTERN OF SNOW INDEX I_s AT 12 GMT, 13 DECEMBER 1958

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REVIEWS

Weather forecasting as a problem in physics, by Andrei S. Monin (translated by Paul Superak). 230 mm × 160 mm, pp. x + 199, *illus.*, The M.I.T. Press, 126 Buckingham Palace Road, London SW1, 1972. Price: £5·65.

Forecasting the weather for a day or two ahead is one of the main tasks of all meteorological services, and forecasting for longer periods is a recognizable task which may have even more importance. It is generally agreed that the method of forecasting with the greatest promise of improvement through research is that loosely described as numerical weather prediction. It has been in operational use for more than a decade and is slowly acquiring its own pedagogical literature, in which the presentation is ordered and polished. The difficulties that held up the early investigators are smoothed away and in the mathematization, which is inevitable since the practical problems are finally arithmetic, much of the physics of atmospheric motions gets lost; the grid scales adopted in practice described the dynamical motions tolerably well but are too large for adequate description of the physics, of which current

knowledge is essentially small-scale. Professor Monin has written a book which surveys the problems associated with numerical weather prediction, both short- and long-range, from the practical point of view of a physicist. In doing so he has restored some of the physical processes to their rightful eminence and shown some of the rents in the apparently respectable cloak of numerical modelling. Few writers have the qualifications of Professor Monin for doing this for he was an early investigator and has maintained his interest for the better part of two decades.

The four chapters which make up the book of less than 200 pages cover a wide variety of topics so that the treatment necessarily is broad rather than detailed and will not appeal to those who need to know the engineering details of models. However, Professor Monin has given nearly 400 references, showing an enviable familiarity with world-wide literature, which indicate where further details may be found. The first short chapter gathers information not easily found on the observed scales of atmospheric motions. The second chapter deals with short-range weather forecasting and is novel in its development and perhaps in its stress on the use of filtered models. Once again it is the background, such as the way in which the various scales of motion react to sudden changes in pressure and wind, that is brought out rather than the structure of any particular model. The third chapter is concerned with global circulation and long-term weather changes and ranges over the observational problem, the physics of the ways in which heat is put into and taken out of the atmosphere, the results from global modelling, the role of the oceans, predictability and extraterrestrial influences. Much of this is not yet textbook material and is certainly open to discussion so that not everyone will agree with the weight that the author attaches to the roles of the physical processes in determining the large-scale developments over long periods; but whether the reader agrees or not a positive starting point for argument is provided. The fourth chapter deals briefly with modelling the planetary circulation and the atmospheres of other planets.

The book is really a substantial review article without pedagogical pretensions and if it is not quite clear at what audience it is aimed, almost all meteorologists are now well enough aware of dynamical methods to be able to profit by reading it. It brings to our notice a great deal of work carried out in the U.S.S.R. which has not been well known in the west, and indeed this is one of the main values of the book.

In translation Professor Monin has a firm, trenchant style and readers will not only profit from but will enjoy reading this book.

E. KNIGHTING

Some environmental problems of livestock housing, WMO *Technical Note* No. 122, by C. V. Smith. 270 mm × 210 mm, pp. xii + 71, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1972. Price: Sw. Fr. 15.

Here is a publication worthy of careful study by all concerned with the housing of livestock. The author, true to the discipline of meteorology, maintains a complete overview of the environmental situation, whilst contemplating in greater detail some of the more specific requirements of livestock housing.

Unfortunately, some material has had to be condensed, and as a result, oversimplification inevitably occurs, particularly in the introductory chapter concerned with establishing the economic and biological motives for housing. Unavoidably too, perhaps, some confusion exists in the frequent use of the term 'environment' when at times it embraces even the unquantifiable elements of stockmanship, and at others only the more specific properties of the aerial environment.

The author, however, leaves no doubt that his real concern is with the latter — the quality, movement and distribution of air in and around livestock buildings. Though there are chapters briefly discussing the thermal and airborne pollutants, e.g. particulates, bacteria, gases, etc. and ventilation systems in general, these are mere precursors to the main sections on air movement.

The effects and patterns of airflow around buildings are discussed with authority but it is unfortunate that some of the data must lose their impact through poor illustration. The data on comparative air patterns resulting from constant-velocity and boundary-layer winds are however gratifying for such information is not readily available to the non-specialist. The movement of air inside the building as a result of air jets, isothermal and non-isothermal motions is neatly packaged in descriptive and mathematical terminology, the latter being perhaps a trifle discouraging to the more casual but interested reader. A short chapter on ventilation rate emphasizes the danger of misinterpreting the concept of air change rate and introduces the more useful quantity — transfer index. This, together with subsequent information on instruments and experimental techniques, provides the research worker at least with some hope for the field measurement of ventilation rate.

The author concludes with a short philosophical note on organizational problems — aimed primarily at the meteorologist, and an extremely useful chapter specifying those technical problems still to be solved. A useful general bibliography finally helps to wrap up a worthwhile contribution to a sadly neglected field.

S. H. BAXTER

NOTES AND NEWS

Meteorological Centenary

The 136-member World Meteorological Organization met in Geneva on 10 September 1973 to celebrate the 100th anniversary of organized international meteorological co-operation. A congratulatory message was received from Dr Kurt Waldheim, Secretary-General, United Nations.

Measurement of the geoid

A new technique for more rapid measurement of the geoid, or mean-sea-level surface, is being evaluated as part of the current SKYLAB mission.

The experiment, which involves the use of a radio-altimeter sensor system, is being conducted by Battelle Columbus Laboratories for NASA's Johnson Space Center (formerly the Manned Spacecraft Center).

According to Zack H. Byrns, technical monitor of the study for NASA, determination of mean sea level is basic to understanding of the ocean and

its environment, particularly for modelling ocean currents, tides, circulation patterns, and air–sea interaction. Improved numerical weather predictions require knowledge of these dynamic ocean parameters, he observes. Navigation, waste disposal and pollution control depend on accurate knowledge of ocean dynamics, as does the understanding of climate.

A. George Mourad, who heads the research team at Battelle Columbus, states that to compute the geoid over the oceans by conventional methods would involve the use of many specially instrumented ships and aircraft over several years — an expensive and time-consuming procedure. Should the radar-altimeter technique prove feasible, the global geoid could be computed much more economically and in a much shorter time.

The altimeter in the SKYLAB experiment is a microwave radar that measures the time for pulsed signals to travel from the space station to the sea surface immediately below it and back to the station. This time is then converted into distances. Knowing the orbit of the SKYLAB accurately over a test area, Mourad comments, it will be possible to compute the geoid.

During the SKYLAB missions the geoid will be determined over selected test areas where the mean sea level has already been determined by the best available conventional techniques. These areas are (a) the North Atlantic bounded by Wallops Island, Bermuda and Florida, (b) the Gulf of Mexico, and (c) the Puerto Rico Trench (north of Puerto Rico).

The Battelle study team will make a comparative analysis and evaluation against the existing geoidal profiles determined by conventional techniques to verify those computed from the SKYLAB altimeter.

Earth Resources SKYLARK Scandinavian survey

A British developed Earth Resources (ER) SKYLARK rocket is standing by for launching from Kiruna, Sweden for a survey of the northern regions of Sweden, Finland and Norway. The launch will take place when there are reasonably cloud-free conditions for clear photography of the area.

The SKYLARK survey is part of a research programme sponsored by the Governments of the United Kingdom, West Germany and Sweden to assess the usefulness of remote sensing of the earth's resources by rocket.

The number of SKYLARK rockets launched to date is 314, and they have had a cumulative success rate of 98 per cent. SKYLARK was originally developed by the Royal Aircraft Establishment in 1957, and since that time it has been continually developed and has been used to carry scientific experiments into the earth's upper atmosphere and beyond. The British Aircraft Corporation co-operated with the Royal Aircraft Establishment in adapting SKYLARK as a camera-carrying platform for Earth Resources survey, and the present system is unique in having particular advantages over other survey methods. It can obtain instantaneous large-area coverage at a fraction of the cost of using an orbiting satellite. The payload is designed and built to the local user's requirements and it can be launched at short notice to coincide with favourable cloud-free conditions.

The Remote Sensing Society — a major new scientific society to be formed

Following a series of meetings in the United Kingdom, the Remote Sensing Society is to be formed. The initiative for this has come from a body of scientists, technologists and administrators deeply interested in methods of measuring and managing the earth's resources and environment.

Remote sensing stems from aerial photography and has been given enormous impetus in recent years by the release of information on previously classified military reconnaissance equipment. Particular interest has been shown in devices which operate at 'invisible wavelengths'. Recent reports on SKYLAB and the Earth Resource Technology Satellite (ERTS) have drawn attention to remote-sensing techniques for monitoring features and phenomena on earth.

A new society is needed because so many branches of science and technology are involved. Inquiries should be directed to Mr R. W. Laing, Public Relations Officer, Remote Sensing Council, at 37 Jessop Road, Stevenage, Hertfordshire.

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